PIVOTAL

February 10, 2017

Mr. Pat O'Brien
Hydrokinetics, Inc.
12975 West 24th Place
Golden, CO 80401

RE: Formation Water Total Dissolved Solids
Pierre Shale (Sussex), Dakota Group and Entrada Formation
ECCV DI-2
Weld County, Colorado

Dear Mr. O'Brien:

Please find attached the total dissolved solids (TDS) estimates for the requested formations based on the offset water samples and ECCV DI-1 well logs. The TDS values were determined from the calculated connate-brine resistivities within the ECCV DI-1.

Please do not hesitate to call me at 720-420-5712 if you have any additional questions or comments.

Sincerely,

Scott Patrick

Scott Patrick
Petroleum Engineer

Attached: *Summary Report*
Connate Brine Resistivity Calculations
Schlumberger Gen-6 Chart

Background

There are a variety of techniques available to calculate formation water saturation, but calculations from logging measurements are the most common due to the wide availability of log data in most wells. Of these techniques, Archie's law is the most common.

Archie's law is a petrophysical model that relates the in-situ conductivity of the formation to its connate-brine saturation and porosity. The electrical conductivity is controlled by the pore system and properties of the pore fluid and is not considered to be impacted by either the formation matrix or fluids other than water such as hydrocarbons. Below is the most common form of Archie's equation:

$$S_w = \left(\frac{aR_w}{R_t \phi^m}\right)^{\frac{1}{n}}$$

Where,

S_w = formation water saturation, decimal
R_w = connate-brine resistivity at formation temperature, ohm.m
R_t = true formation resistivity (deep log resistivity), ohm.m
ϕ = formation porosity, decimal
a = tortuosity factor, decimal
m = cementation exponent, decimal
n = saturation exponent, decimal

While Archie's equation is primarily used to determine water saturation, it can be used to solve for any of the formation properties within the equation. In this case, the connate-brine resistivity (R_w) is required to estimate the total dissolved solids for regulatory classification.

$$R_w = \frac{R_t \phi^m {S_w}^n}{a}$$

The true formation resistivity, R_t, and porosity, ϕ, are obtained from log measurements, and, in a water-saturated interval, the water saturation, S_w, can be assumed to be 100% (effectively making the saturation exponent, n, irrelevant). However, the Archie parameters m and a need to be calibrated utilizing measured water samples.

Methodology

For the ECCV DI-2 well, total dissolved solids for the Sussex member of the Pierre Shale, Dakota Group, and Entrada were estimated from log measurements in the ECCV DI-1 because open hole logs are not available for the DI-2.

To begin, the cementation exponent, m, was determined in the offsetting wells, where water samples were taken. The cementation exponent is ranges between 1.7 and 4.1, but for sandstones, the value tends to range closer 2.0. The tortuosity factor, a, can vary between 0.5 and 1.5, but to reduce the number of unknowns, it was fixed at 1.0, which was Archie's original assumption. True formation resistivity and formation porosity were acquired from the relevant well logs. These readings were taken from intervals considered to be clean sands as indicated from the gamma ray log.

The water saturation was assumed to be 100% unless the resistivity suggested the presence of hydrocarbons. A water saturation assumption of 100% also eliminates the need to determine the saturation exponent, n, as it has no impact on the calculations. Two wells with samples from the Dakota group had elevated resistivity readings, which indicated the presence of hydrocarbons. In these two wells, the water saturation was assumed to be 40% and the saturation exponent to be 2.0. However, these wells were not used in the average value of the cementation exponent, but did support the values used.

Once the cementation exponent was determined from the water sample and log data, the values were averaged and then utilized with the ECCV DI-1 log measurements to estimate the connate-brine resistivity at the formation temperature.

The connate-brine resistivity and formation temperature were then used to determine the equivalent NaCl concentration from Schlumberger's Gen-6 Chart (attached).

Results

The determination of the cementation exponent for each well and zone with a water sample are provided in Tables A1-A3. The calculated values for m fall between 1.9 and 2.5, which is an acceptable range for sandstone formations. Tables A1-A3 also include the calculation of the connate-brine resistivity for each of the zones of interested based on the ECCV DI-1 log measurements. The estimated total dissolved solids for each desired formation based on the calculated connate-brine resistivities are provided in Table 1.

Table 1: Estimated Total Dissolved Solids for ECCV DI-1 Formations.

Formation	Connate-Brine Resistivity @ Formation Temperature	Total Dissolved Solids
Pierre Shale (Sussex)	0.08 ohm.m @ 186 °F	33,000 ppm
Dakota	0.15 ohm.m @ 257 °F	10,500 ppm
Entrada	0.09 ohm.m @ 268 °F	19,500 ppm

Application in Other Geologies

It should be noted that limestones and formations containing clays such as shales face additional challenges in developing reliable models. The complex pore systems found in limestones can cause the cementation exponent, m, to have a much larger acceptable range compared to sandstone.

The presence of clays presents a larger challenge. Clays significantly complicate the application of water saturation models based on electrical properties. The cation exchange capacity (CEC) of clays impacts the electrical properties of the matrix such that Archie's assumptions are no longer valid. Several water saturation models attempt to account for the presence of clays in shaley sands, but there are no models specifically developed for shales using standard log measurements. Any successful attempt at calculating the connate-brine water resistivity in a shale would require significant amounts of both core analysis and water samples, neither of which are generally available.

Due to these factors, determining the TDS in the other formations present between the Fox Hills and Lyons is not considered reliable.

Table A1: Sussex Member of the Pierre Shale Formation Connate-Brine Resistivity Calculations

Well Name	Donald Miller B 4	Emery 31-13 1	Nesssu 7	Richard Hein 1	ECCV DI-1
COGCC Facility ID	150344	150128	150186	150222	- -
Location (Sec., Township, Range)	4, 1N, 67W	13, 1N, 68W	20, 2N, 66W	21, 2N, 66W	1, 1S, 66W
Well API	05-123-08969	05-123-08846	05-123-07763	05-123-10302	- -
Depth	4,674	4,757	4,578	4,650	4,950
Water Sample Total Dissolved Solids (ppm)	17,708	17,625	24,187	18,700	- -
True Formation Resistivity (ohm.m)	10	15	11	4	4.5
Formation Porosity (%)	14%	10%	13%	16%	14%
Temperature (°F)	136	172	160	153	186
Cementation Exponent, m (-)	2.15	2.00	2.20	1.90	2.06
Formation Water Saturation, S_w (%)	100%	100%	100%	100%	100%
Connate Brine Resistivity, R_w @ Formation Temperature	0.15	0.15	0.12	0.12	0.08
Water Sample Resistivity @ Formation Temperature	0.15	0.15	0.12	0.12	- -

Table A2: Dakota Formation Connate-Brine Resistivity Calculations

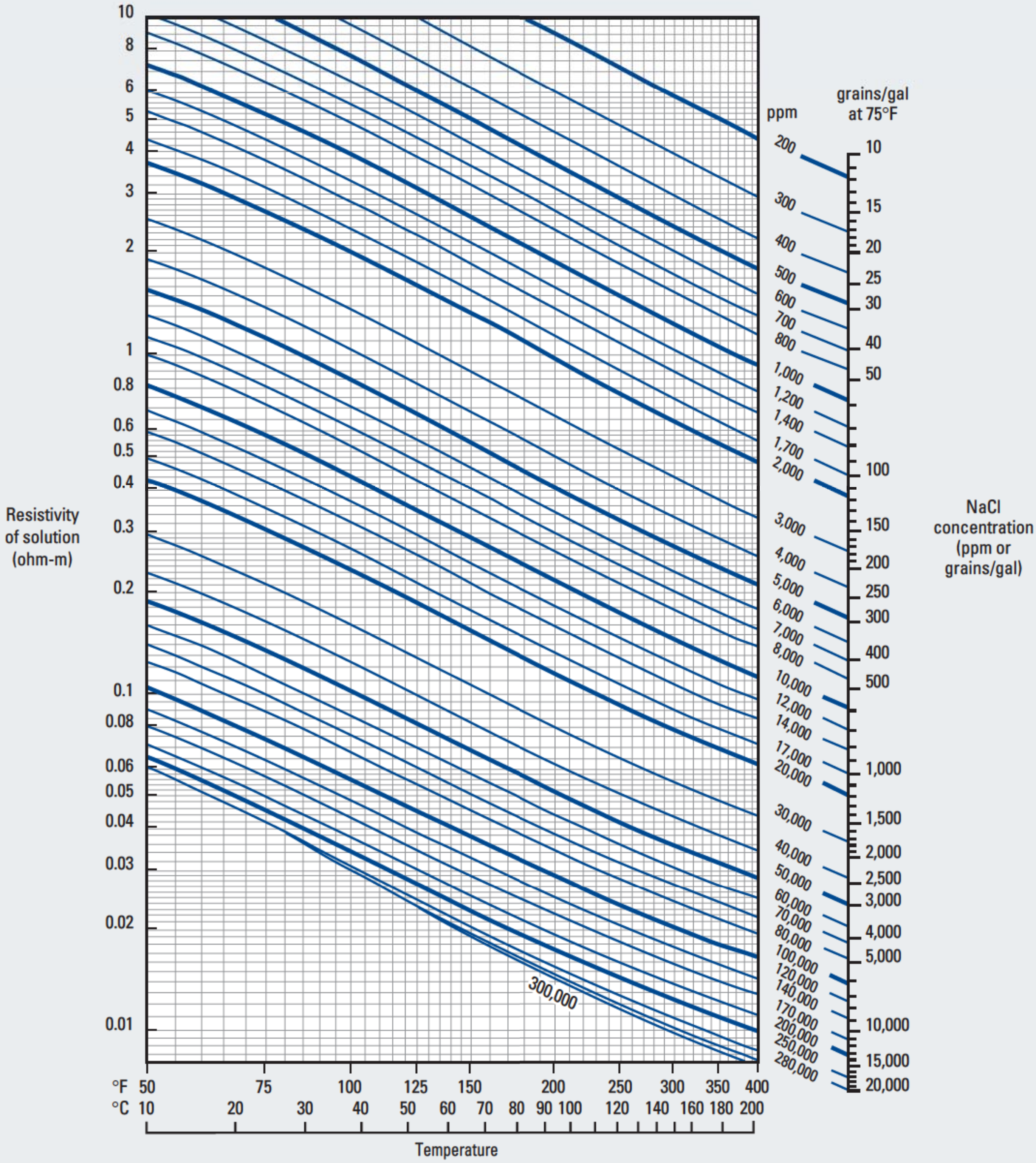
Well Name	UPRR Antelope Farms 23-27	Gale 1	Champlin 100 Amoco A 7	Downing 24-1	Cowell 1	Champlin 100 Amoco A 7	ECCV DI-1
COGCC Facility ID	150191	159075	150010	150247	159052	150010	- -
Location (Sec., Township, Range)	27, 2S, 63W	30, 1N, 63W	17, 3S, 58W	24, 3S, 59W	31, 3S, 59W	17, 3S, 58W	1, 1S, 66W
Well API	05-001-08697	05-123-11275	05-001-08066	05-001-06677	05-001-06908	05-001-08066	- -
Depth	7,606	7,414	5,942	6,221	6,239	5,880	7,987
Water Sample Total Dissolved Solids (ppm)	22,960	13,662	10,958	11,495	11,630	10,647	- -
True Formation Resistivity (ohm.m)	180	15	20	25	60	30	13
Formation Porosity (%)	8	9	13	12	16	11	12
Temperature (°F)	220	221	174	184	171	173	257
Cementation Exponent, m (-)	2.30	2.00	2.18	2.23	2.15	2.18	2.14
Formation Water Saturation, S_w (%)	40	100	100	100	40	100	100
Connate Brine Resistivity, R_w @ Formation Temperature	0.09	0.15	0.23	0.22	0.23	0.24	0.15
Water Sample Resistivity @ Formation Temperature	0.09	0.15	0.23	0.22	0.23	0.24	- -

Table A3: Dakota Formation Connate-Brine Resistivity Calculations

Well Name	KMG 16-24i	Wattenberg SWD 1	LSWD 1	HPD Platteville 1	ECCV DI-1
COGCC Facility ID	159433	159110	159372	159270	- -
Location (Sec., Township, Range)	24, 2N, 65W	19, 2N, 66W	18, 3N, 54W	24, 3N, 66W	1, 1S, 66W
Well API	05-123-37996	05-123-15621	05-123-30367	05-123-29168	- -
Depth	8,192	8,444	8,104	8,546	8,488
Water Sample Total Dissolved Solids (ppm)	10,490	17,400	14,000	14,650	- -
True Formation Resistivity (ohm.m)	10.0	8	9	11	35
Formation Porosity (%)	11%	11%	16%	17%	6%
Temperature (°F)	240	251	232	260	268
Cementation Exponent, m (-)	1.85	1.90	2.30	2.50	2.14
Formation Water Saturation, S_w (%)	100%	100%	100%	100%	100%
Connate Brine Resistivity, R_w @ Formation Temperature	0.17	0.11	0.13	0.12	0.09
Water Sample Resistivity @ Formation Temperature	0.17	0.11	0.13	0.125	- -

Resistivity of NaCl Water Solutions

Conversion approximated by $R_2 = R_1 [(T_1 + 6.77)/(T_2 + 6.77)]°F$ or $R_2 = R_1 [(T_1 + 21.5)/(T_2 + 21.5)]°C$



© Schlumberger

◄ ► Back to Contents